AN INVESTIGATION OF THE USE OF INDUCTION GENERATORS IN AIRCRAFT ELECTRICAL SYSTEMS

BY

JOHN PEYTON HOBSON

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PREFACE

This paper is a theoretical investigation of the practical use of induction generators in 3 phase 400 cycle aircraft electrical systems. No particular installation was intended although the generator capacity is on the order of new machines currently being developed for use in the near future.

Since no induction motors of the power and frequency ratings desired are at present in existance such a machine was designed. However, only the electrical part of the design was considered although reasonable estimates of total weight and dimensions were necessary.

It is the author's desire to acknowledge the assistance given by Professors C.V.O. Terwilliger and W.C. Smith and to thank collectively the members and students of the Electrical Engineering Department of the Postgraduate School.

This work was performed between December 1950 and June 1951 at the United States Naval Postgraduate School, Annapolis, Maryland.

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TABLE OF SYMBOLS AND ABBREVIATIONS

AT	Ampere turns
B	Magnetic flux density
Bc	Corrected gap density
Bc1	Stator core flux density
Bc2	Rotor core flux density
Bt1	Stator tooth flux density
Bt2	Rotor core flux density
E	Voltage
f	fringing constant
H	Watts /cubic inch/ ^{o}Centigrade
I	Current in amperes
I1	Primary current
I2 = Ib	Secondary current
Iba	Average secondary current
Irm	Maximum current in end rings
Ir	R.m.s. current in end rings
K1	Slot contraction factor
Kd	Duct contraction factor
kb	Belt factor
kp	Pitch factor
l	Armature length
le	Equivalent armature length
lc	Length of end connections
N1	Number of primary conductors
N2	Number of rotor bars
Nt	Number of slots

n	Frequency
$2p$	Number of poles
p'	Number of phases
$P'h$	Hysteresis loss; watts /cubic inch
$P'e$	Eddy current loss; watts /cubic inch
$Pk2$	Total watts lost in rotor
$r1$	Stator resistance
r_2	Rotor resistance
r	Total resistance (r1 r2)
S	Slots/phase/pole
s	Slip
T	Temperature rise, degrees centigrade
Tss	Starting torque in synchronous watts
Ts	Starting torque in foot-pounds
U	Perimeter of phase belt bundle
v	Synchronous peripheral velocity
X	Total reactance (X1 X2)
$X1$	Stator reactance
$X2$	Rotor reactance
Xm	Magnetizing reactance
λ_p	Pole pitch
λ_t	Tooth pitch
δ	Radial depth of air gap
ϕ	Total flux
Δ	Peripheral current density
$a1$	Equivalent stator tooth tip
$a2$	Equivalent rotor tooth tip
C	Conductors per slot

d	Diameter
acp	Coil pitch ÷ pole pitch

CHAPTER I

INTRODUCTION

During the years since the beginning of World War II the electrical demand in both military and commercial aircraft has increased almost without limit. In 1940 the average load per aircraft engine was about two kilowatts while the present contemplated load today is of the order of thirty kilowatts per engine.

Up to the present day aircraft electrical systems have been primarily direct current with major emphasis being given to the twenty-eight volt system. In an effort to reduce the weight of copper conductors and to attain greater generator capacity higher voltages became necessary. And, since high altitudes make commutation and contact operation extremely difficult it was necessary to adopt an alternating current system.

This system is a nominal 208/120 volt, 3 phase, 400 cycle system. However, since the alternators are driven by the airplanes' main engines very precise constant speed drives are necessary if the alternators are to be paralleled. Such a drive is presently in use by both the United States Navy and the United States Air Force, but it weighs as much as the alternator which it drives.

This paper proposes the use of induction generators coupled to the main engines through suitable variable speed drives and connected in parallel with a constant frequency source such as an inverter. Such a system would

have the following advantages:

(1) The system frequency would be independent of generator speed.

(2) The generator speed would be determined by the load demand which is more readily sensed than frequency.

(3) The induction generator with exciting condensers is lighter than an equivalent alternator.

(4) Since an induction generator has a high rotor resistance to achieve the desired characteristics, it has a high starting torque and so can serve as the main engine starter, thus eliminating that item completely.

Induction generators, on the other hand, have the disadvantage that they will not provide any reactive power. However, it is this author's belief that the weight of copper saved will compensate for the condensers used at the loads to achieve unity power factor.

CHAPTER II

MACHINE DESIGN

Since no 400 cycle induction motors of large ratings were available with which to conduct tests, the electrical design phase of such a machine was completed. The results of this design follow:

Output	40 kw = 53.6HP
Phases	3
Terminal voltage	208
Frequency	400
Full load efficiency	0.88
Full load power factor (as motor)	0.92
Armature connection	Star
Current per phase	137.2
Number of poles	8
Synchronous rpm	6000
Gap density	
As motor	23,450
As generator	25,500
Diameter	10 inches
Length	3.93 inches
Pole pitch	3.93 inches
Induced voltage	
As motor	115
As generator	125
Total number of slots	96
Total number of active conductors	192
Active conductors per phase	64
Peripheral current density	839

Net length of iron	3.54
Fraction net iron length	0.9
Tooth pitch	0.327
Width of tooth tip	0.207
Tooth tip density	
As motor	41,200
As generator	44,800
Width of Slot	0.12
Slot opening	0.12
Section primary conductor in c.m.	25,450
Conductor dimensions	0.1 x 0.2
Insulation thickness	0.01
Depth of slot	0.5
Slot space factor	0.667
Fraction slot width	0.367

Core

Thickness of laminations	0.01
Radial depth back of slot	1.0
Maximum density	
As motor	51,200
As generator	55,600
Outside diameter	13
Volume of core (excluding teeth)	122.3
Hysteresis watts per cubic inch	
As motor	2.74
As generator	3.13
Eddy watts per cubic inch	
As motor	4.2
As generator	4.96
Total watts lost in core	
As motor	850
As generator	990

Width of tooth 1/3 from narrow end	0.214
Max density at same point	
As motor	39,900
As generator	43,400
Volume of primary teeth	34.8
Hysteresis Watts per cubic inch	
As motor	1.84
As generator	2.02
Eddy watts per cubic inch	
As motor	2.54
As generator	3.01
Total watts lost in teeth	
As motor	152.5
As generator	175.0
Total primary iron loss	
As motor	1002.5
As generator	1165

Copper

Fraction active conductor	0.444
Length primary conductor per phase	566
Hot resistance per phase	0.0222
Primary copper loss	1255
Total Primary losses	
As motor	2257.5
As generator	2420.0

Heating

Peripheral Surface	189
Watts per sq. in. per degree cent.	0.09
Temperature rise, deg. cent.	
As motor	133
As generator	142.5
Slip at full load	
As motor	0.1
As generator	-0.1

Speed at full load	
As motor	5400
As generator	6600
Pulley Torque in lb-ft	
As motor	52.1
As generator	42.6

<u>Squirrel Cage Rotor</u>

Number of slots	90
Tooth pitch	0.349
Amperes per slot	256
C.M. per ampere	174
Rotor bar section in C.M.	44500
in sq.in.	0.035
Dimensions of bar	0.1 x 0.35
Total depth of slot	0.56
Width of slot	0.12
Slot opening	0.04
Width of tooth tip	0.229
Width of tooth 1/3 from narrow end	0.214
Equivalent length of 1 bar	4.0
Total length of bars	360
Total watts lost in bars	2120
Total watts in rotor conductors	4000
Watts lost in end rings	1880
Average Amperes per bar	231
Max amperes in end rings	1300
RMS amperes in end rings	919
Total res. of end rings	.00223

Total length of end rings	59.6
Section in c.m	107,000
Section in square inches	0.084
Dimensions of end rings	.24 x .35
Secondary resistance at primary	0.285

Core

Radial depth back of slots	1.0
Maximum density	
As motor	51200
As generator	55600
Inside diameter of core	7 in.
Volume of core excluding teeth	89
Secondary frequency	40
Hysteresis watts per cubic inch	
As motor	.274
As generator	.313
Eddy watts per cubic inch	
As motor	.042
As generator	.05
Total watts lost in core	
As motor	28.2
As generator	32.3

Teeth

Max density 1/3 from narrow end	
As motor	42500
As generator	46200
Volume of rotor teeth	34.6
Hysteresis watts per cubic inch	
As motor	.203
As generator	.232
Eddy watts per cubic inch	
As motor	.029
As generator	.034
Total watts lost in rotor teeth	
As motor	8.03
As generator	9.2

Total rotor iron loss	
As motor	36.23
As generator	41.5
Total iron loss	
As motor	1038.7
As generator	1206.5
Total rotor loss	
As motor	4036
As generator	4041

Heating

Peripheral surface	194
Watt per sq.in. per degree cent.	0.148
Temperature rise	139°C

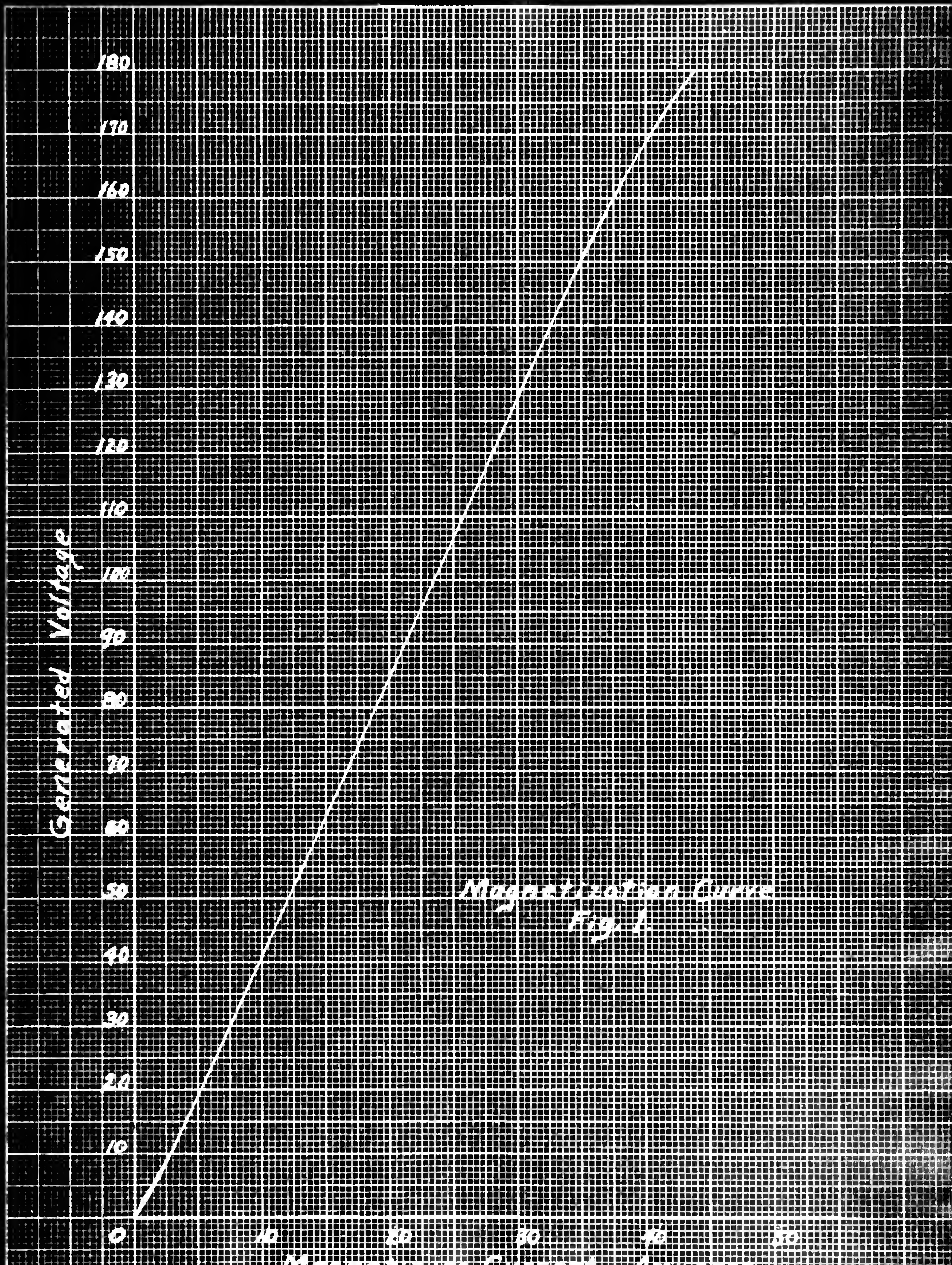
Air Gap

Radial depth of air gap	0.02
Primary tooth fringing constant	1.3
Width of primary tooth tip	0.207
Equivalent primary tooth tip	0.263
Fraction equivalent primary tooth tip	0.805
Secondary tooth fringing constant	0.6
Width of secondary tooth tip	0.229
Equivalent secondary tooth tip	0.253
Fraction equivalent secondary tooth tip	0.725
Slot contraction factor	0.584
Equivalent length of armature core	3.95
Contraction factor (3.95 ÷ 3.93)	1.005
Corrected maximum gap density	
As motor	40,000
As generator	43,500

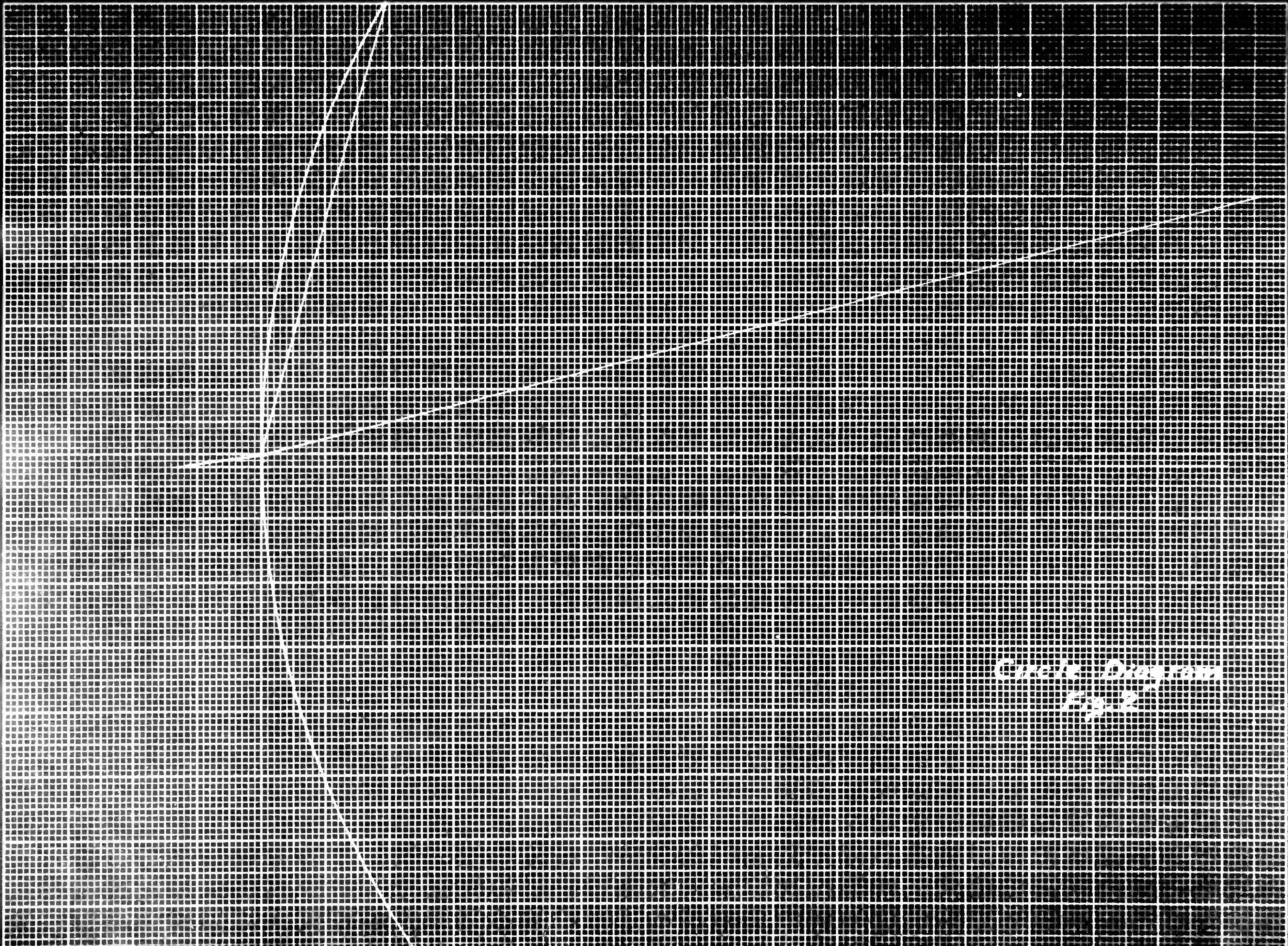
E	B_g	AT	B_{c1}	AT	B_{T1}	AT	B_{c2}	AT	B_{T2}	AT	AT_T	I_m	X_m
5	1740	21.8	2225	3.3	1735	0.5	2225	2.6	1850	0.5	28.7	1.46	3.43
10	3480	43.5	4450	5.0	3470	0.8	4450	3.6	3700	0.8	57.3	2.73	3.67
20	6960	87.0	8900	6.6	6940	1.1	8900	4.8	7400	1.1	100.6	5.11	3.91
30	10440	130.5	13350	8.0	10410	1.3	13350	5.8	11100	1.3	146.9	7.46	4.02
40	13920	174	17800	9.3	13880	1.5	17800	6.8	14800	1.5	193.1	9.81	4.08
50	17400	217.5	22250	10.2	17350	1.7	22250	7.4	18500	1.7	238.5	12.11	4.13
60	20880	261	26700	11.2	20820	1.8	26700	8.2	22200	1.9	284.1	14.4	4.16
70	24360	304.5	31150	12.1	24290	1.9	31150	8.8	25900	2.0	329.3	16.7	4.19
80	27840	348	35600	12.9	27760	2.1	35600	9.4	29600	2.1	374.5	19.0	4.21
90	31320	391.5	40050	13.7	31230	2.2	40050	10.0	33300	2.3	419.7	21.3	4.22
100	34800	435	44500	14.3	34700	2.3	44500	10.4	37000	2.4	464.9	23.6	4.24
110	38280	478.5	48950	14.8	38170	2.4	48950	10.8	40700	2.5	509.0	25.6	4.26
120	41760	522	53400	15.4	41640	2.5	53400	11.2	44400	2.6	553.7	28.1	4.28
130	45240	565.5	57850	16.0	45110	2.6	57850	11.7	48100	2.7	598.5	30.4	4.29
140	48720	609	62300	16.5	48580	2.7	62300	12.0	51800	2.8	643.0	32.6	4.29
150	52200	652.5	66750	17.1	52050	2.8	66750	12.5	55500	2.9	687.8	34.9	4.27
160	55600	696	71200	20.4	55520	2.9	71200	14.8	59200	3.0	737.1	37.4	4.22
170	59100	739.5	75650	27.5	58990	3.0	75650	20.0	62900	3.0	793.0	40.3	4.10
180	62600	783	80100	44	62460	3.1	80100	32	66600	3.1	865.1	43.9	[illegible]
190	66000	826.5	84550	66	65930	3.2	84550	48	70300	3.2	946.8	48.1	[illegible]
200	69600	870	89000	88	69400	3.7	89000	64	74000	4.0	1029	52.3	3.83

Magnetization Data

Table I



180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
Generated Voltage
Magnetizing Current - Amperes
Magnetization Curve
Fig. 1



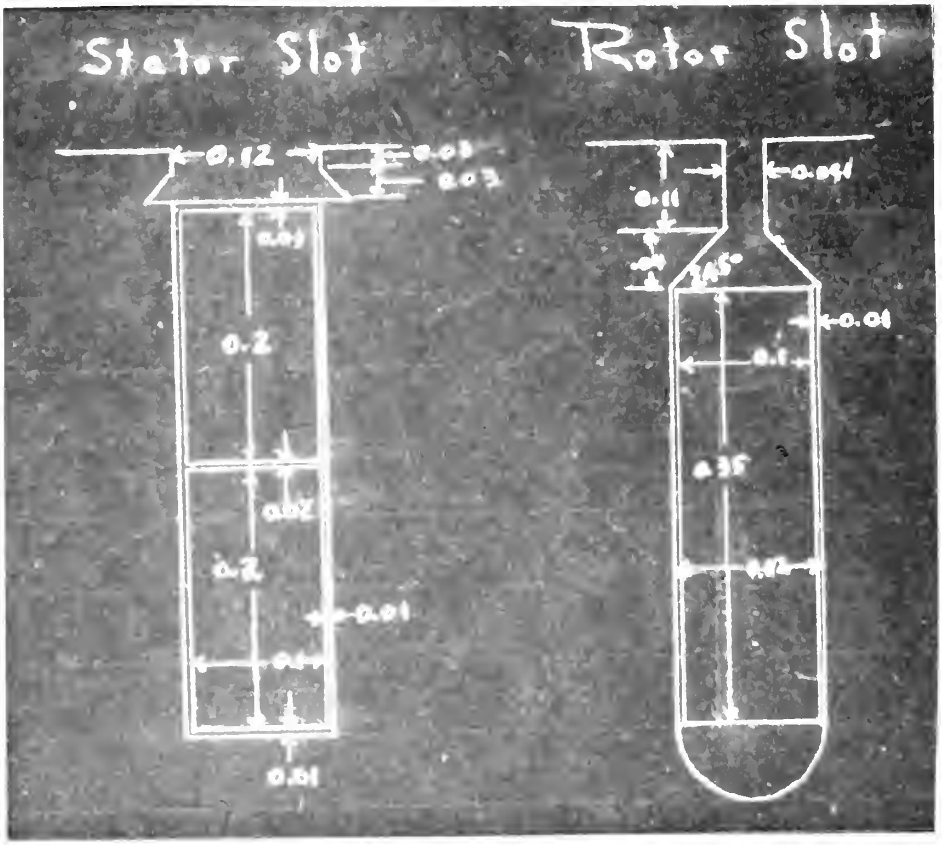
Circle Diagram
Fig. 2

Constants

Exciting reactance	4.27
Exciting resistance	35.8
Primary resistance	0.0222
Secondary resistance	0.285
Total resistance	0.3072
Primary reactance	0.0716
Secondary reactance	0.0152
Total reactance	0.0868
Leakage factor	0.0199

Breakdown and Starting

Slip at breakdown	3.18
Starting current	376
Starting torque	
Synchronous watts	120,000
Pound feet	140
Volume primary conductor	11.32 cubic inches
Volume rotor bars	12.6
Volume rotor end rings	5.01
Volume all copper	28.93
Weight all copper	9.29 pounds
Volume stator core	122.3 cubic inches
Volume stator teeth	34.8
Volume rotor core	89.0
Volume rotor teeth	34.6
Volume all iron	280.7
Weight all iron	79.7 pounds
Weight all active material	89 pounds

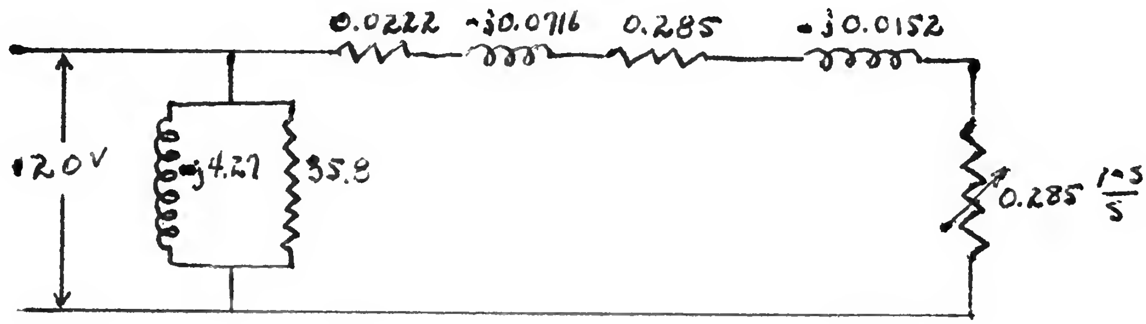

Stator Slot
Rotor Slot
0.12
0.2
0.02
0.2
0.01
0.01
0.11
45°
0.01
0.35

Weight inactive material (estimated)	9
Total weight	98 pounds

CHAPTER III

PERFORMANCE

Although the important part of the circle diagram of this machine is included in this chapter (fig.2) its size precludes its use in determining the performance. Therefore, the performance of the machine as a generator has been calculated from the constants of the machine. All calculations were made using the following equivalent circuit:



For selected values of slip between -0.005 and -0.4 the current, Icba, in the secondary necessary for a phase voltage of 120 volts was determined. Using this current the generated voltage was then calculated and the corresponding values of the exciting current taken from the magnetization curve.

The variable resistive losses in the rotor and stator were added to the assumedly fixed iron losses to determine the overall efficiency. The output power current is the secondary current less the fixed core loss current.

Using the exciting current, the secondary current, and the total reactance the total reactive volt amperes

required by the generator were determined.

Figure 3 is a plot of exciting current, efficiency, load current per phase, and inverter load (assuming unity power factor and 85 microfarads per phase across the generator terminals) plotted against slip.

From Table III it is seen that at rated load of 111 amperes per phase each induction generator requires 16,500 reactive volt amperes in addition to the lagging reactive volt amperes required by the load.

Present Bureau of Aeronautics Standards specify 0.8 lagging power factor for all a.c. loads. This means 30,000 volt amperes for 40 kilowatts of power. In other words, if this machine is to deliver 40,000 watts some other source must provide 56,500 reactive volt amperes.

The recent advancements in the manufacture of barium titanite ceramic condensers makes their use admirably suitable for this purpose. Such condensers can now be fabricated which weigh not more than 0.03 lbs per microfarad or occupy more than 0.07 cubic inches per microfarad.

An aircraft electrical load of 40,000 watts may be reduced to unity power factor by the use of 276 microfarads of capacity which if distributed at the loads should not weigh more than 15 lbs. If this capacity is placed at the load the weight of conductor may be reduced by 20%, a reduction in weight far exceeding the weight of condensers used.

S	$r_2 \frac{1-s}{s}$	$r_1 + r_2$	$r_1 + \frac{r_2}{s}$	$x_1 + x_2$	Z	E	I_2	E_2
[illegible]	-57.3	0.301	-57	0.087	57	120	2.1	120
[illegible]	-28.8	0.301	-28.5	0.087	28.5	120	4.21	121
	-14.5	0.301	-14.2	0.087	14.2	120	8.45	122.7
	-9.18	0.301	-9.41	0.087	9.41	120	12.7	124.2
	-7.41	0.301	-7.10	0.087	7.10	120	16.9	125.2
	-5.99	0.301	-5.68	0.087	5.68	120	21.1	126.3
	-4.31	.301	-4.05	0.087	4.05	[illegible]	29.6	[illegible]
	-3.14	0.301	-2.83	0.087	2.83	[illegible]	42.4	[illegible]
	-2.36	.301	-2.35	0.087	2.35	[illegible]	51	[illegible]
	-2.11	.301	-1.88	0.087	1.88	120	63.8	[illegible]
	-1.11	.301	-1.60	0.087	1.60	120	75.[illegible]	[illegible]
	-1.71	[illegible]	-1.40	0.087	1.40	[illegible]	85.6	[illegible]
	-1.55	.301	-1.24	0.087	1.24	[illegible]	96.8	[illegible]
	-1.42	[illegible]	-1.11	0.087	1.11	[illegible]	[illegible]	[illegible]
	-1.32	.301	-1.01	0.087	1.015	[illegible]	[illegible]	[illegible]
	-1.24	[illegible]	-0.91	0.087	0.92	[illegible]	[illegible]	[illegible]
[illegible]	-1.16	[illegible]	-0.85	0.087	.854	1[illegible]	[illegible]	[illegible]
	-1.1[illegible]	[illegible]	-0.79	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	-1.045	.3[illegible]	-0.738	0.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-.4	-1.0	.301	[illegible].69	[illegible]81	[illegible]	1[illegible]	[illegible]	[illegible]

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[illegible]	I_{c+h}	I_L	$3I_L^2$ [illegible]	P_{c+h}	P_{out}	P_{in}	η
1	3.35	0.86	16.4	1206	309	1531	0.202
[illegible]	3.35	5.1	65.7	1206	1814	3086	0.588
[illegible]	3.35	9.35	148.5	1206	3364	4720	0.713
[illegible]	3.35	13.55	263	1206	4886	6360	[illegible]
1.1	3.35	17.75	411	1206	6394	[illegible]	[illegible]
	3.35	26.25	807	1206	9444	1146[illegible]	
	3.35	39	1653	[illegible]	14064	[illegible]	
	3.35	41.6	2394	[illegible]	17164	[illegible]	
	[illegible]	[illegible]	375	[illegible]	21744	[illegible]	
	[illegible]	[illegible]	517	[illegible]	25200	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
		[illegible]			[illegible]		
	[illegible]	[illegible]			[illegible]		
	3.35	[illegible]	[illegible]		[illegible]		
	3.35	[illegible]					
	3.35	[illegible]			[illegible]		
	[illegible]	[illegible]			[illegible]		
	[illegible]	[illegible]				[illegible]	

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S	I_2	E_2	I_m	EI_m	$.087 I_2^2$	VAR_p	VAR	I_L
	[illegible]	121	28.4	3385	1.5	3385	10236	0.86
	[illegible]	123	28.7	3410	6.2	3412	10353	5.1
	[illegible]	124	29.0	3445	14.0	3451	10482	9.35
	[illegible]	125	29.2	3480	24.8	3494	10590	1[illegible].55
	[illegible]	126	29.5	3505	38.6	3517	10737	17.15
		127	30.1	3540	78.6	3[illegible]84	11067	[illegible]
		133	31.0	3610	156	[illegible]16	11628	[illegible]
		131	32.0	3720	226	4[illegible]	12198	[illegible]
		14[illegible]	32.6	3840	353	[illegible]	12790	[illegible]
		143	33.4	3910	488	[illegible]	13500	[illegible]
		1[illegible]	[illegible]	4010	634	[illegible]	14150	[illegible]
		[illegible]	[illegible]	4080	[illegible]14	[illegible]	15050	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15960	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	

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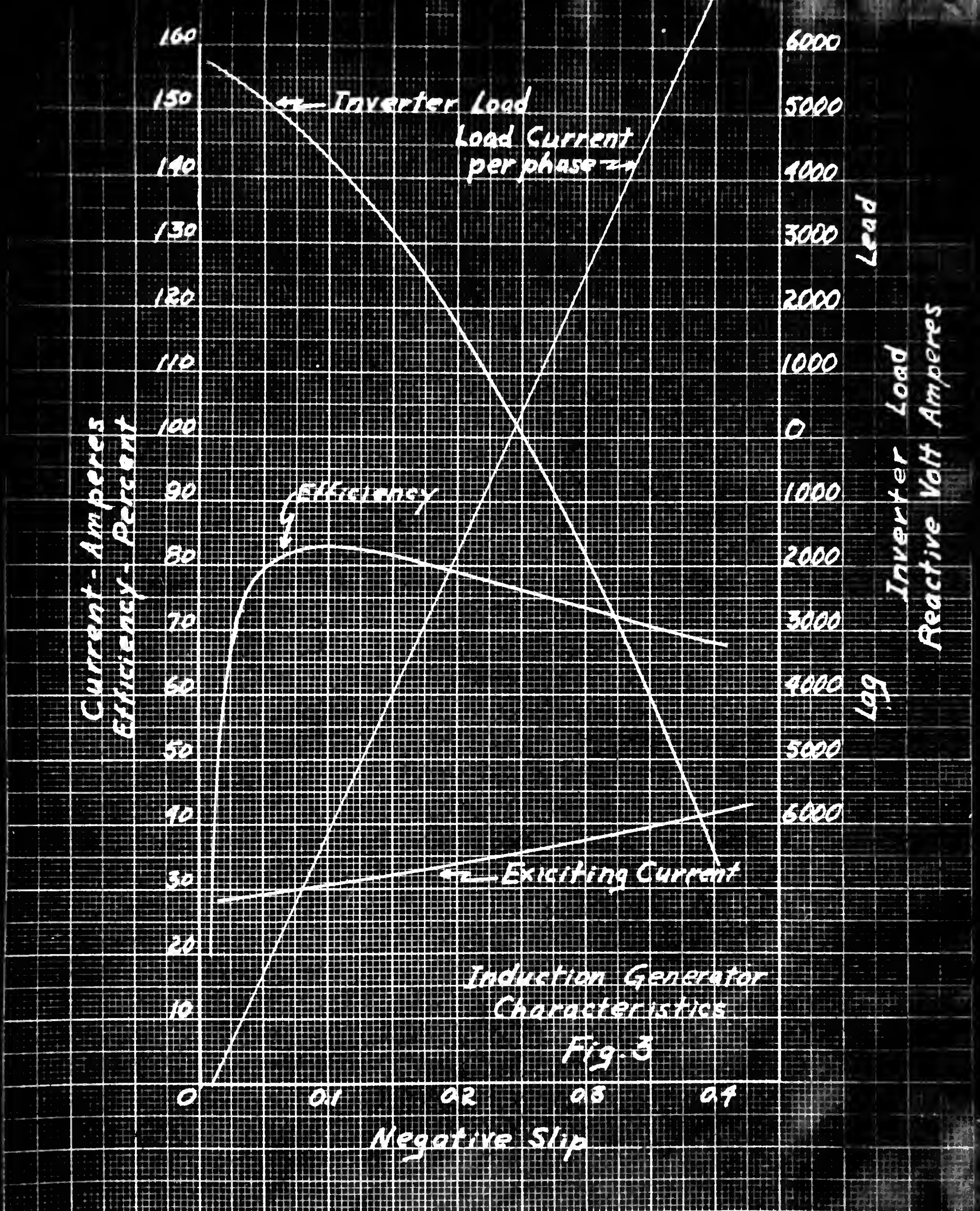


Inverter Load
Load Current per phase
Efficiency
Exciting Current
Induction Generator Characteristics
Fig. 3
Current - Amperes
Efficiency - Percent
Log Inverter Lead Load
Reactive Volt Amperes
Negative Slip
0
0.1
0.2
0.3
0.4
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
6000
5000
4000
3000
2000
1000
0
1000
2000
3000
4000
5000
6000

At this point, the constant frequency source must still supply 16,500 reactive volt amperes at full load and 20000 at 50% overload. If three condensers of 49 microfarads each are connected in delta across the terminals of the induction generator its requirements become 5000 VA leading at no load, zero at full load and 5000 VA lagging at 50% overload. These condensers should not weigh more than six pounds or occupy more than 11 cubic inches.

From the design of the machine it was found that as a motor this particular machine developed a starting torque of 140 ft-lbs and had a rated torque of 52.1 ft-lbs at 5400 rpm. Such a motor would be excellent for use as a starter motor for aircraft engines. The displacement of the d.c. starter motor represents a saving of approximately 90 lbs. on each engine.

CHAPTER IV

CONCLUSION

In the case of any new proposal it is desirable to compare it with equivalent equipment presently fulfilling the same purpose. Assuming a theoretical aircraft having a maximum load requirement of 40 kilowatts from each generator the following results are obtained in regard to weight:

Unit	Alternator	Induction Gen.
Generator	120	98
Condensers	0	21
Voltage regulator	9	0
Constant Speed Drive	75	75
Conductor	45	35
Inverter	40	120
Starter	85	0
4 KW 28^V d.c. supply	25	25
Batteries	55	55
Total	454	429

Although the above figures show an advantage of only 25 pounds in favor of the induction generator system, it is the author's belief that other advantages weigh even more heavily in its favor.

Since the induction generator has no brushes the problem of brush and slip ring wear at high altitudes is non-existent. The inverters necessary to the system

could be located in a pressurized section of the fuselage so as to reduce this problem in that equipment.

Since power is more easily sensed than frequency the control of the variable speed drive could be simplified. Small variations in generator speed will produce changes in load distribution but no circulating currents will exist unless a machine drops to or below synchronous speed.

The induction machine being basically a simpler more rugged machine than the synchronous type it should be both cheaper to build and more durable in service.

APPENDIX

The following formulae were used in the design of this machine:

$$E = 8.06\ kbkpVlNB\ 10^{-8}$$

$$\Delta = NI \div \pi d$$

$$\lambda p = d \div 2p$$

$$\lambda t = d \div Nt$$

$$Ph' = 2\ \frac{n}{100}\ (Bm^{10^{-5}})\ 1.6$$

$$Pe'' = (n\ Bm\ t\ 10^{-5})^2$$

$$l1'' = 1 + 1.5\ Acp\lambda p$$

$$Hl = (1 + 0.02v) \div 60$$

$$Tl = Pl \div H_1S_1$$

$$Pk2 = 7465\ HP \div N$$

$$\Delta = 1.23\quad 10^{-8} \div kp\ Bd^2 l$$

$$Ib = 1.01\ \Delta \lambda_{t_2}$$

$$Iba = Ib \div 1.11$$

$$Ir = Nt2\quad Iba \div 4\quad 2\ P$$

$$r_2 = Pk2 \div (I\ \eta\ p.f.)^2$$

$$f = 0.6 + 1.47\ \log\ (Sol \div 2\quad)$$

$$tl = ttl + 2\ f.\ \delta$$

$$al = tl \div \lambda_{t_1}$$

$$a2 = t2 \div \lambda t2$$

$$Kl = A.A2$$

$$le = 1 + \delta - Nd\ (Wa - 2fd\ ) = 1 + \delta$$

$$Kd = le \div 1$$

$$Bc = B \div KlKd$$

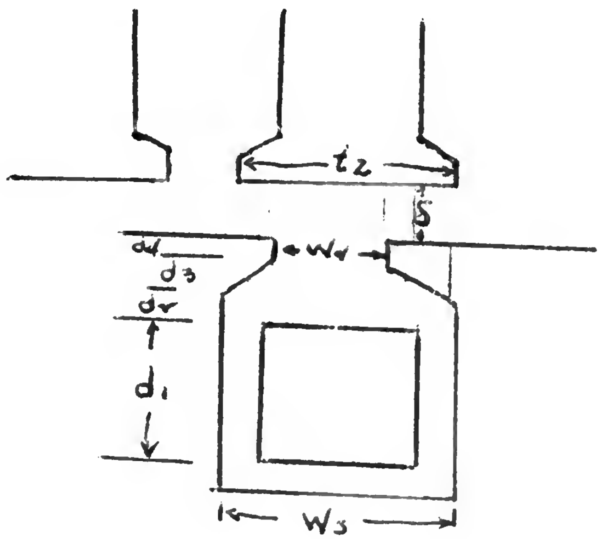
$$ATg = 0.626\ Bc\ \delta$$

$$x_1 = 2\pi f 10^{-8} k_b k_p p S_1 C_1^2 N\phi_1 l$$

$$N\phi_1 = 3.19\left[\frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4+w_3} + \frac{d_4}{w_4}\right] + 3.19\,\frac{t_2-w_4}{6\delta} + \frac{l_c}{l}\left[.146\log\frac{\pi l_c}{u} + 0.064\right]$$

$$x_2 = 2\pi f 10^{-8} k_p k_b p S_2 C_2^2 N\phi_2 l\left[\frac{C_1 S_1}{C_2 S_2}\right]^2$$

$$N\phi_2 = 3.19\left[\frac{d_1}{3w_3} + \frac{d_2}{w_3} + \frac{2d_3}{w_4+w_3} + \frac{d_4}{w_4}\right] + 3.14\,\frac{t_1-w_4}{6\delta} + \frac{l_c}{l}\left[.146\log\frac{\pi l_c}{u} + 0.064\right]$$



p = no of poles

S = slots /phase/ pole

C = conductors/slot

U = perimeter of phase belt bundle

lc = length of end connections

Is $= E \div \sqrt{r^2 + x^2}$

Tss = p'Is^2

Ts = 0.117 p Tss ÷ n

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